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Assessment of Thermal and Mechanical Properties of Cement-Based Materials—Part 2: Perlite Concrete

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Abstract: There is an international concern for reducing energy consumption and protecting the environment in the construction industry. The energy efficiency of a building depends on the thermal resistance of concrete, and utilizing concrete products with elevated thermal resistance can enhance this aspect. This study analyzes the impact of perlite, as an addition, on the physico-mechanical properties of concrete, with the aim of identifying perlite concrete products that will respond to the improvement of the heat transfer resistance of the building envelope. The study examines the effect of replacing different amounts of concrete aggregates with perlite in percentages of 10%, 20%, 30%, and 100%. The results show that substituting sand with perlite improves the thermal performance of concrete, but its mechanical properties are negatively affected. The research carried out highlighted that perlite can be successfully introduced in the production of concrete blocks used for external non-bearing wall panels, the outstanding feature being the reduction of energy consumption in buildings. Overall, the paper identifies an efficient and environmentally friendly way of using perlite in the construction industry, enhancing the energy efficiency of buildings while minimizing the environmental footprint caused by the construction industry.

Keywords: sustainability; cement-based materials; concrete; perlite; physico-mechanical properties; energy performance

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1. Introduction

The concrete industry has many opportunities regarding the development of products that achieve the goals of zero-energy consumption in buildings, drastically reducing the carbon footprint and ensuring the environmental protection requirements. Concrete with high thermal resistance as a cement-based material can significantly contribute to improving the energy efficiency performance of a building. As mentioned in the first part of the study [1], in which crumb rubber concrete was analyzed as a cement-based material, in order to reduce the thermal conductivity of concrete and improve its insulation properties, it is necessary to examine the options for increasing the thermal performance of concrete by using other types of materials with heat-insulating properties, in building envelope components, while minimizing the environmental footprint. Concrete is a material widely used in the construction industry, the raw materials in its compositions being natural aggregates, cement, water, and admixtures. Aggregates represent approximately 60-75% of the concrete mixture by volume, and cement and water make up the rest. Therefore, in the research studies carried out in the laboratory, various secondary raw materials (wastes) were explored, as alternatives, in order to minimize the effect of concrete on sustainability and reduce environmental pollution, following the trend of global initiatives [2], by prioritizing the use of materials with higher thermal performance in

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construction and renovation of buildings [3], as well as through waste recycling. Prioritizing the efficient and economical utilization of resources has gained importance nowadays [4].

Perlite, a naturally occurring alumino-siliceous amorphous volcanic material derived from crude perlite rock, is commonly used in construction and is found in various countries, including Italy, Hungary, Turkey, Greece, Japan, and the United States [5–7]. The global production of perlite is increasing, driven by rising demand. As such, material producers in the perlite industry need to improve perlite waste collection and create an economically viable system encouraging its use.

Expanded perlite stands out as a favorable option due to its characteristic of low density for the production of lightweight concrete [8]. The extensive body of research in building materials technology has consistently shown that incorporating expanded perlite as an aggregate in concrete leads to significant enhancements in various concrete attributes, including weight reduction and enhanced thermal insulation [9–12]. These findings, supported by various references, underscore the justification for utilizing expanded perlite in lightweight concrete applications [13–16]. However, the industrial application of perlite in concrete remains relatively limited [8].

The substitution of natural aggregate with expanded perlite in mixtures has been shown to reduce their thermal conductivity due to the porous structure of the perlite [17–31]. The thermal conductivity of perlite significantly impacts the reduction of thermal conductivity in perlite concretes [26], with an increase in the content of expanded perlite leading to a greater reduction. According to Oktay et al. [32], incorporating 10%, 20%, 30%, 40%, and 50% volume of 0.15-11 mm perlite particles as a substitute for natural sand led to thermal conductivity reductions of 22.96%, 38.01%, 64.23%, 74.36%, and 81.48% in the concretes, respectively.

The research on perlite concrete has shown that replacing natural sand with expanded perlite can significantly reduce the density of the mixture, with some studies reporting reductions of up to 65.46 % [21]. According to the research conducted by Türkmen and Kantarcı [33,34], partially replacing natural sand with perlite (0-4 mm size) at volumes of up to 15% reduces the unit weight of the concrete mixture that is less than 1.36 %. At higher levels of perlite substitution (over 50 %), the density of the mixture can decrease by as much as 500 kg/ m^3 due to perlite's low specific gravity [20], which reduces the unit weight of the mixture. Although the decreased density of perlite concrete can offer benefits, it can also lead to lower mechanical properties [17–31].

Compressive strength is an essential characteristic of concrete when used as a construction material. Studies have found that partially substituting natural sand with perlite can lead to a significant decline in the 28-day compressive strength of the resulting concrete mixture [35,36]. For instance, one study found that replacing natural aggregate with perlite (0.15-11mm size) at levels of 10 %, 20 %, 30 %, 40 %, and 50 % resulted in a reduction in compressive strength of 39.8 %, 63.33 %, 80.69 %, 84.29 %, and 90.58 %, respectively [33]. Incorporating expanded perlite as an aggregate in concrete mixtures can increase porosity, which can lower the density and strength of the mixture [17–31].

In light of the information mentioned above, the objective of this paper is to examine the behavior of perlite concrete, highlighting the impact of the use of perlite on the properties, in order to identify some construction products with characteristics that innovatively combine only the positive results obtained in the laboratory research carried out. Even though there are many different studies on perlite concrete, there is a lack of specific application areas for this material.

The research aims to find solutions for using this cement-based material, in which perlite has replaced sand, to make masonry blocks as building envelope elements. To analyze perlite concrete in detail, an experimental program was implemented to study its general behavior, including density, compressive strength, thermal conductivity, and microscopic characteristics.

2. Materials and Methods

In this study, the perlite granules (Figure 1) utilized in the concrete mixture had a size of 0-4 mm size and were not subjected to any form of treatment. In the used form, the perlite granules can be manufactured products, or from waste on the construction site that can be reused. They have the same material properties, as well as the size of the granules from 0 to 4 mm.

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Figure 1. Perlite granules.

As mentioned in the first part of the study regarding the assessments of thermal and mechanical properties of cement-based materials in which the crumb rubber concrete was analyzed [1], the laboratory tests for the perlite concrete use the same control concrete mixture composition [1]. A water/cement ratio (W/C) of 0.55 was used in the concrete compositions, (control or with perlite). The components of the control concrete mix are shown in Table 1, being similar to that used in previous study, [1]. The control concrete composition resulted with characteristics determined for strength class C 20/25, exposure class XC3 XA1 and consistency class S3.

Based on the review of previous research and the fact that the perlite granules range in size from 0-4 mm, samples were prepared with three distinct mixture compositions where 10%, 20%, and 30% of the 0-4 mm aggregate were substituted with perlite granules. The percentage of replacement of the aggregates with perlite granules was determined by equivalent volume (the volume of replaced sand is equal to the volume of perlite). Table 1 displays the amounts of constituent materials used in the control concrete and perlite concrete.

Table 1. Component materials for 1 m^3 of control concrete and of perlite concrete.

Case study	**Water** (l)	**Cement (CEM I 42.5R)** (kg)	**Aggregate 0-4 mm** (kg)	**Aggregate 4-8 mm** (kg)	**Aggregate 8-16 mm** (kg)	**Perlite** (kg)
C 20/25 [1]	180	330	764	317	783	0.00
S1—10 % perlite	180	330	732	317	783	2.32
S2—20 % perlite	180	330	700	317	783	4.64
S3—30 % perlite	180	330	668	317	783	6.96

Cubic samples were prepared for each composition to evaluate the concrete mixtures' compressive strength and thermal conductivity properties. According to the standardized methodology, these samples had a height and width of 150 mm and were tested 28 days after being poured into the molds. After 28 days, the samples underwent thermal conductivity testing using a portable device, the ISOMET 2114. This device has a surface sensor designed for hard materials and uses a dynamic investigation method to quickly measure the thermo-mechanical characteristics of the samples [1]. The dynamic method involves applying temperature changes to the sample and measuring the resulting heat flow. The temperatures of the sample are recorded periodically over time, allowing the calculation of the thermal conductivity based on the temperature changes and the heat flow through the sample. According to [37], ISOMET 2114 is a hand-held measuring instrument for directly measuring heat transfer properties of various materials, including cellular insulating materials, plastics, glasses, and minerals. The calibration coefficient stated in the sense of the standard ASTM – 5334-08 may be applied to subsequent measurements automatically [37]. Calibration data in internal memory ensure the interchangeability of probes without affecting measurement accuracy [37].

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The compressive strength of a material is a measure of its resistance to deformation under a compressive load. In this study, the samples were tested for their compressive strength using a testing machine, the ZwickRoell SP1000 hydraulic equipment [1]. The tests were conducted according to standard EN 12390-3:2009 requirements and protocols. The compressive force was applied to the samples perpendicular to the pouring orientation, with a loading speed of 0.2 MPa/s and an accuracy of less than 1% [1].

3. Results

3.1. Density

After completely hardening the samples, their weight and volume were measured to calculate their density (ρ = m/V). The results were calculated for the four mixture compositions and are presented in Table 2. Analyzing the results, the perlite concrete samples have a lesser density than the control samples, with a reduction of 4.45 % in the case of 10 % perlite, 5.89 % in the case of 20 % perlite, and 7.83 % in the case of 30 % perlite.

Table 2. The density of the concrete mixtures based on the proposed formulation.

Case study	**Density, [ρ]** Average values (kg/m³)	**Decreasing** (%)
C 20/25 [1]	2295.92	-
S1—10% perlite	2193.53	4.45
S2—20% perlite	2160.57	5.89
S3—30% perlite	2116.05	7.83

3.2. Thermal conductivity

To understand the influence of the perlite in the concrete mixture, it is mandatory to analyze it from the standpoint of thermal conductivity. Concluding reports were provided with completed characteristic thermomechanical measurements, including thermal conductivity coefficient, [W/mK]. Measurements were taken on all sides of each cubic sample to ensure accuracy and validate the results. The samples were subjected to thermal conductivity testing using the ISOMET 2114 (Figure 2).

(a) **(b)**

Figure 2. Measure the thermal conductivity values of the samples with the ISOMET 2114: (a) the display of ISOMET 2114 (b) the measuring device for hard surface of ISOMET 2114.

As previously reported in the study on crumb rubber concrete [1], the thermal conductivity measurements for control samples vary from 2.05 W/mK to 2.26 W/mK for a heat flow parallel to casting and from 2.48 W/mK to 2.58 W/mK for a heat flow perpendicular to casting direction [1]. The findings indicate that the thermal conductivity parallel to casting is 13-20 % higher than the average measured thermal conductivity values in the perpendicular direction [1] (see Table 3).

Table 3. The thermal conductivity of the composition in the control mixture [1].

Case study	**Thermal conductivity, [λ]**	
	Heat flow direction versus casting direction	
	Parallel (average value) (W/mK)	Perpendicular (average value) (W/mK)
C 20/25	2.55	2.16

The samples of perlite concrete mixture with 10 % of the sand replaced with perlite were subjected to tests for thermal properties. Thermal conductivity measurements presented in Table 4 vary from 2.14 W/mK to 2.30 W/mK for heat flow perpendicular to the casting and 2.52 W/mK for heat flow parallel to the casting direction. In comparison, the thermal conductivity measurements in the parallel direction exhibit a 14.6% increase over the average thermal conductivity values obtained when heat flows perpendicularly to the casting. The improvement in the thermal conductivity, meaning, in fact, a decrease, is insignificant compared to the control samples. The results show a decrease of lower than 1% (from 2.55 W/mK to 2.52 W/mK) (see Figure 3).

The thermal properties of the concrete mixtures were tested after replacing 20 % and 30 % of sand with perlite, and the results are documented in Table 4. When 20 % of the fine aggregates were replaced with perlite, the thermal conductivity measurements spanned from 2.12 W/mK to 2.15 W/mK for heat flow perpendicular to the casting and 2.44 W/mK for heat flow parallel to the casting direction (Table 4). Upon analyzing the readings, it becomes evident that the thermal conductivity value is 14.2% greater than the average thermal conductivity measurements obtained for heat flow perpendicular to the casting direction. There was a 4.7% decrease in thermal conductivity for heat flow parallel to the casting direction (from 2.55 W/mK to 2.44 W/mK) and 1.2 % for heat flow perpendicular to the casting (from 2.16 W/mK to 2.13 W/mK) compared with the control samples, (Figure 3).

The samples with the replacement of 30 % of sand with perlite were also subjected to measurements (Table 4). Thermal conductivity measurements vary from 2.07 W/mK to 2.25 W/mK for heat flow perpendicular to the casting and 2.41 W/mK for heat flow parallel to the casting direction. It is noticed that the thermal conductivity for heat flow parallel to the casting direction is 13.6 % higher than the average of the thermal conductivity measurements perpendicular to the casting. The concrete mixture with a 30% perlite replacement improved thermal conductivity compared to the control samples. There was a 6% decrease in thermal conductivity for heat flow parallel to the casting direction (from 2.55 W/mK to 2.41 W/mK) and a 1.9% decrease for heat flow perpendicular to the casting direction (from 2.16 W/mK to 2.12 W/mK), as depicted in Figure 3.

The study concludes that the thermal conductivity of the perlite concrete mixture decreases by an average of 3 % as the perlite ratio increases from 10 % to 30 %.

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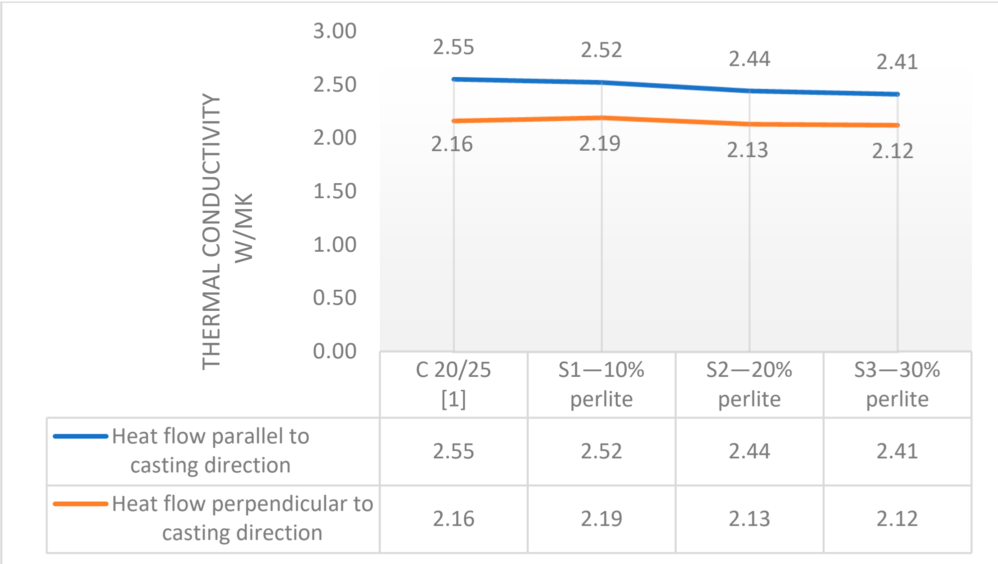

Figure 3. Graphic representation for the correlation of the thermal conductivity of perlite concrete and control concrete C20/25.

Table 4. The thermal conductivity of the perlite concrete mixtures.

Case study	Parallel (W/mK)	Perpendicular (W/mK)				
		Side 1	Side 2	Side 3	Side 4	Average
S1—10 % perlite	2.52	2.19	2.30	2.14	2.16	2.20
S2—20 % perlite	2.44	2.13	2.15	2.14	2.12	2.14
S3—30 % perlite	2.41	2.09	2.07	2.25	2.07	2.12

(Table spanning headers: **Thermal conductivity, [λ]**; Heat flow direction versus casting direction)

3.3. Compressive strength

Compressive strength is the primary parameter used to evaluate concrete's mechanical properties, which measures how much force a material can withstand before it breaks or crushes. Determining the material's strength class is based on the compressive strength value. The samples underwent uniaxial compression using a hydraulic testing machine to evaluate the compressive strength of the four different concrete mixture compositions (see Figure 4). The compressive strength of the samples was then calculated based on the testing results.

(a) **(b)** **(c)** **(d)**

Figure 4. The test of compressive strength: (a) C20/25 [1] (b) S1—10% perlite (c) S2—20% perlite (d) S3—30% perlite.

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The C20/25 samples used in this study and those examined in the crumb rubber concrete study [1] exhibit an average compressive strength value of 25.98 MPa. In contrast, the perlite concrete samples display values of 24.23 MPa (10 %), 23.80 MPa (20 %), and 22.44 MPa (30 %) (Table 5). For a 10 % ratio, the decrease in compressive strength is relatively small, at 6.75 %. However, as the ratio of perlite increases to 20 % and 30 %, the reduction in compressive strength becomes more significant, with decreases of 8.40 % and 13.66 %, respectively.

Table 5. The compressive strength of perlite concrete compared to that of C20/25 concrete.

Case study	Compressive strength, [R_c] (MPa)	Decreasing in percentage (%)
C 20/25 [1]	25.98	
S1—10 % perlite	24.23	6.75
S2—20 % perlite	23.80	8.40
S3—30 % perlite	22.44	13.66

The outcomes of the compressive strength tests for the concrete mixture with perlite replacements were consistent with previous research on the topic. As the proportion of perlite increases, there is a decline in the compressive strength of the concrete mixture. This reduction in compressive strength was expected, as previous studies have also reported a similar trend.

3.4. The variation of the physico-mechanical characteristics of the perlite concrete upon the total replacement of the 0-4 mm sort with perlite

Previous research investigations into incorporating perlite in concrete concentrated on replacing a certain percentage of the fine fraction of the aggregate to determine its impact on the thermal conductivity of the resulting mixture. However, these studies did not observe a significant improvement in thermal conductivity. The deterioration of the compression resistance below the limit that would have allowed the use of perlite concrete in structural elements, led to the new direction of research for this type of material: to have increased thermal insulation properties, but with use in non-structural products. As a result, the scope of the research was expanded to 100 % replacement of 0-4 mm aggregate with perlite. This allowed for a more thorough investigation into the potential benefits of using perlite in concrete products, concrete having a lower stregth class of C16/20.

Two sets of concrete compositions were prepared, each consisting of cubic samples possessing a side length measuring 150 mm. These samples were analyzed for both their thermal conductivity and compressive strength. The first set of samples was a control, using the standard C16/20 class concrete mixture composition without any replacements. The choice of the resistance class was made on the basis of previous research, which allowed the approximation of the ratio of the compressive strength decrease, when using perlite to replace sand, so that, for the concrete products (blocks) used in non-load-bearing walls, the compressive strength should present values in accordance with the requirements of the norms.

The second set of samples used perlite to completely replace the 0-4 mm aggregate. The perlite was evenly distributed throughout the concrete mixture during the mixing process using a concrete mixer. Thermal conductivity measurements were conducted on every side of each sample to ensure accurate data, and the average of these measurements was used in the analysis.

Uniaxial compression tests were conducted by subjecting the samples to a perpendicular compressive force during the pouring process to assess the compressive strength of the control concrete and perlite concrete. The tests were carried out using a WAW-600E press with a loading speed of 0.2 MPa/s. The obtained data revealed that the average compressive strength of the control samples stood at 20.96 MPa, whereas the average compressive strength of the perlite samples was measured at 18.55 MPa. Consequently, the findings underscored a decrease in compressive strength by 11.49% compared, as indicated in Table 6.

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Table 6. Compressive strengths of perlite concrete and control concrete of class C16/20.

Case study	Compressive strenght, [R_c] (MPa)	Decreasing in percentage (%)
C 16/20	20.96	-
S4—100 % perlite	18.55	11.49

The density of the concrete mixture with the perlite replacement was determined, and the results revealed a substantial decrease in density compared to the original mixture, as listed in Table 7.

Table 7. The average density of the researched mixtures.

Case study	Density, [ρ] (kg/m^3)	Decreasing (%)
C 16/20	2290.42	-
S4—100% perlite	1938.78	15.35

The thermal conductivity of the control samples was measured for heat flows parallel and perpendicular to the casting direction. The values for these measurements ranged from 1.72 W/mK to 2.3 W/mK for heat flow perpendicular to the casting direction and from 2.04 W/mK to 2.27 W/mK for heat flows parallel to the casting direction (Table 8). These values are similar to those obtained in an earlier set of control samples (as listed in Table 3). It was observed that the thermal conductivity for heat flows parallel to the casting direction exhibited a slightly greater magnitude than the average thermal conductivity values for heat flows perpendicular to the casting direction, with a 1-4% difference.

Table 8. The thermal conductivity values corresponding to the composition of the control mixture.

Case study	Thermal conductivity, [λ]				
	Heat flow direction versus casting direction				
	Parallel (W/mK)		Perpendicular (W/mK)		
C 16/20—sample 4	2.27	2.13	2.20	2.13	2.21
C 16/20—sample 5	2.04	2.06	1.72	1.98	2.30
C 16/20—sample 6	2.15	1.96	2.21	2.17	2.25
average	***2.15***		***2.11***		

In addition to the measurements on the control samples, the thermal conductivity of the concrete mixture with perlite was also determined. The values for these measurements ranged from 1.12 W/mK to 1.64 W/mK for heat flows perpendicular to the casting direction and from 1.17 W/mK to 1.5 W/mK for heat flows parallel to the casting direction (Table 9).

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Table 9. The thermal conductivity values of concrete mixtures containing perlite.

Case study	**Thermal conductivity, [λ]**				
	Heat flow direction versus casting direction				
	Parallel (W/mK)		Perpendicular (W/mK)		
S4-1—100%perlite	1.41	1.51	1.12	1.30	1.54
S4-2—100%perlite	1.17	1.62	1.36	1.49	1.35
S4-3—100%perlite	1.50	1.40	1.34	1.42	1.64
average	***1.36***		***1.42***		

In comparison to the control samples, the concrete mixture with perlite significantly improved thermal conductivity. For the heat flow parallel to the casting, there was an improvement of 36.74 % (from 2.15 W/mK to 1.36 W/mK). For the heat flow perpendicular to the casting surface, there is an improvement of 32.7 % (from 2.11 W/mK to 1.42 W/mK) (Figure 5).

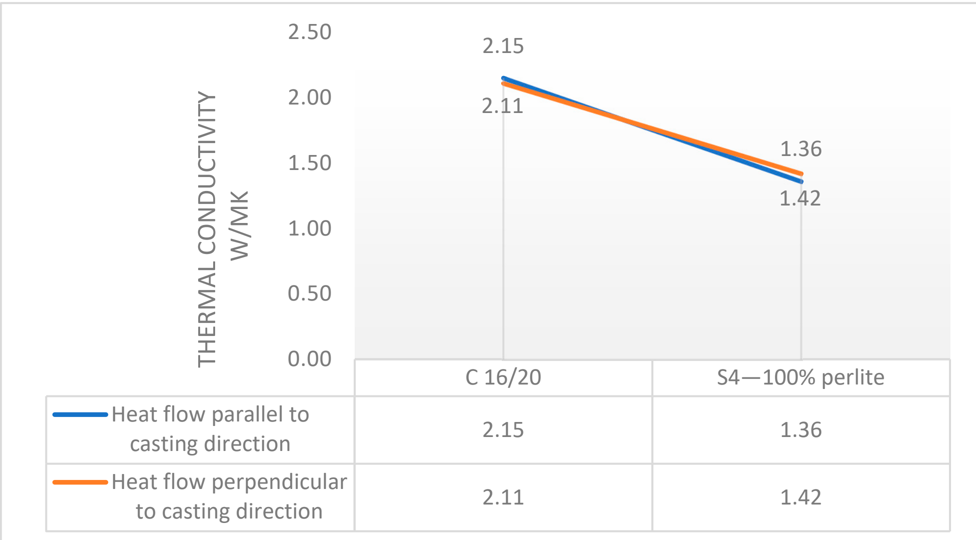

Figure 5. Graphic for comparing the thermal conductivity of perlite concrete and control concrete C16/20.

3.5. The influence of perlite concrete with 100% sand replacement on a thermal bridge

The compression strength of perlite concrete with 100% replaced sand classified the material as class C12/15, which is suitable for its use in non-structural products/elements. A possible use of it can be in the masonry blocks from which the panels can be made for the non-load-bearing walls in a building envelope. The building's performance relies significantly on the envelope's thermal resistance. The areas in the envelope that adversely influence energy consumption and thermal comfort are the areas with reduced thermal resistance, known as thermal bridges. In this context, a study on the impact of perlite concrete on the indicators that characterize thermal bridges (the studied parameters being the heat flows) can substantiate its use in manufactured blocks for masonry.

The thermal bridge located at the intersection of the outer wall with the terrace slab (exterior corner area) was selected. A compared analysis for thermal bridge evaluation when clay bricks (case I) and perlite concrete blocks (case II) were used for the masonry of the exterior wall panels was performed, Figure 6, [38,39]. The characteristic data for the main materials used as input parameters are presented in Table 10, and for other materials are presented in Table 11 [38,39]. The analysis was done using specialized programs for the design and analysis of thermal bridges, as well as for the presentation of the geometric and technical details of the structure. The software utilized in this study

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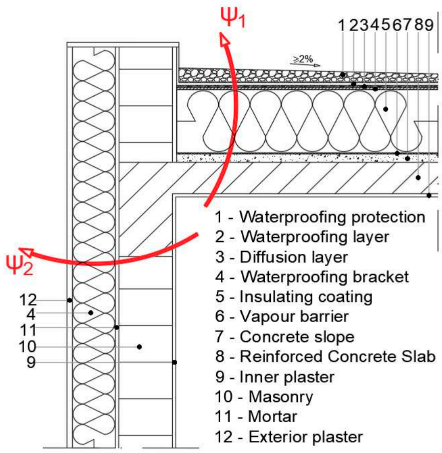
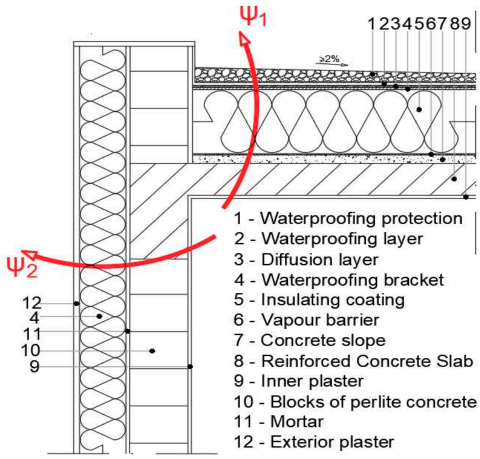
included Autocad for generating graphical models and RDM 6.17 for obtaining heat flow results for each analyzed case [40,41]. Table 12 presents the linear thermal bridge coefficients evaluated by using RDM 6.17, while Figure 7 visually represents the corresponding legend of the results on value fields.



(a)



(b)

Figure 6. Pictures for corner thermal bridge: (a) Case I – with clay bricks; (b) Case II – with perlite concrete blocks, [38,39].

Table 10. Characteristic data of main materials used.

Materials	Thickness, [d] (m)	Density, [ρ] (kg/m³)	Coefficient of thermal conductivity [λ] (W/mK)	Mass heat capacity [C] (J/kgK)
Reinforced concrete slab	0.150	2500	2.16	840
Clay bricks	0.250	1800	0.80	870
Perlite concrete blocks	0.250	1939	1.42	1035

Table 11. Characteristic data of other materials, [38,39,42].

Materials	Thickness, [d] (m)	Density, [ρ] (kg/m³)	Coefficient of thermal conductivity [λ] (W/mK)	Mass heat capacity [C] (J/kgK)
The material properties for the envelope with a terrace roof				
Inner plaster	0.015	840	0.870	1700
Reinforced concrete slab	0.150	2500	2.160	840
Concrete slope	0.020	1800	0.930	840
Vapour barrier	0.010	1700	0.380	1460
Insulating coating	0.300	20	0.044	1460
Waterproofing bracket	0.010	1800	0.930	840
Diffusion layer	0.010	600	0.170	1460
Waterproofing layer	0.015	600	0.170	1460
Waterproofing protection	0.100	1800	0.700	840
The material properties for the exterior wall				

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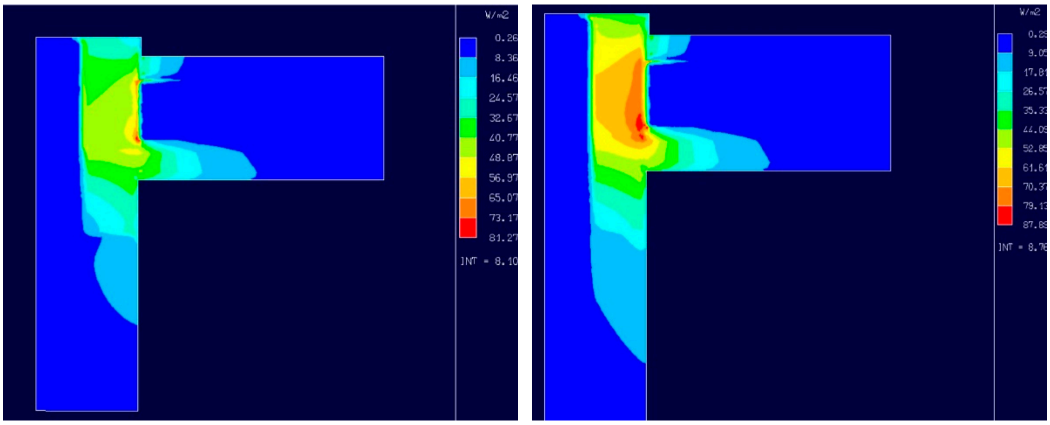
Inner plaster	0.015	840	0.870	1700
Insulating coating	0.200	20	0.044	1460
Mortar	0.035	1800	0.930	840
Exterior plaster	0.025	840	0.870	1700

Table 12. Linear thermal bridges coefficients, Ψ.

Thermal bridge	ϕ (W/m)	ΔT (°C)	B (m)	$R_{element}$ (m²K/W)	ψ (W/m²C)
Thermal bridge **Case 1 - roof**	13.6	38	1.20	6.974	0.185
Thermal bridge **Case 1 - wall**	15.98	38	1.20	5.079	0.184
Thermal bridge **Case 2 - roof**	15.89	38	1.20	6.974	0.246
Thermal bridge **Case 2 - wall**	19.03	38	1.20	4.943	0.258



(a) **(b)**

Figure 7. Linear thermal bridges coefficients: (a) Case I (clay bricks); (b) Case II (perlite concrete blocks), [40,41].

The results obtained for the analyzed thermal bridge also demonstrate a positive influence on the thermal performance, comparing the values obtained for the wall panel made of clay bricks and perlite concrete blocks. The thermal flow values show a 16% increase in the wall panel for case II without reaching the critical values (Figure 7). The overall thermal resistance of the wall ($R_{element}$) with perlite concrete blocks (case II) shows a decrease of only 3% compared to the resistance of the wall made with bricks (case I). Based on the results, it can be concluded that the perlite concrete blocks have a good thermal transfer behavior through the external walls, especially in the critical areas defined as thermal bridges.

3.6. The bonding of perlite within the concrete composition.

To ensure that the perlite particles were evenly distributed throughout the concrete mixture, special care was taken to distribute the perlite evenly during the concrete mixing process in a concrete mixer. Furthermore, the mixture made by replacing the fine aggregate with perlite required special attention during the pouring and vibration of the molds to ensure a uniform distribution of the aggregates and achieve coagulation of the mixture. Throughout the compressive strength tests, fissures were seen in the regions of the samples with the highest concentration of perlite. However, when the samples had undergone press testing, it was observed that the perlite particles were mostly evenly arranged in the mixture. To investigate the bonding between the perlite and the other components of the concrete mixture, 1 cm fragments of each composition were examined under a microscope using a Large Field Detector in low vacuum mode (LFD). As shown in Figure 8, the bonding between the regions with perlite and the remaining aggregates was reasonable compared to conventional concrete.

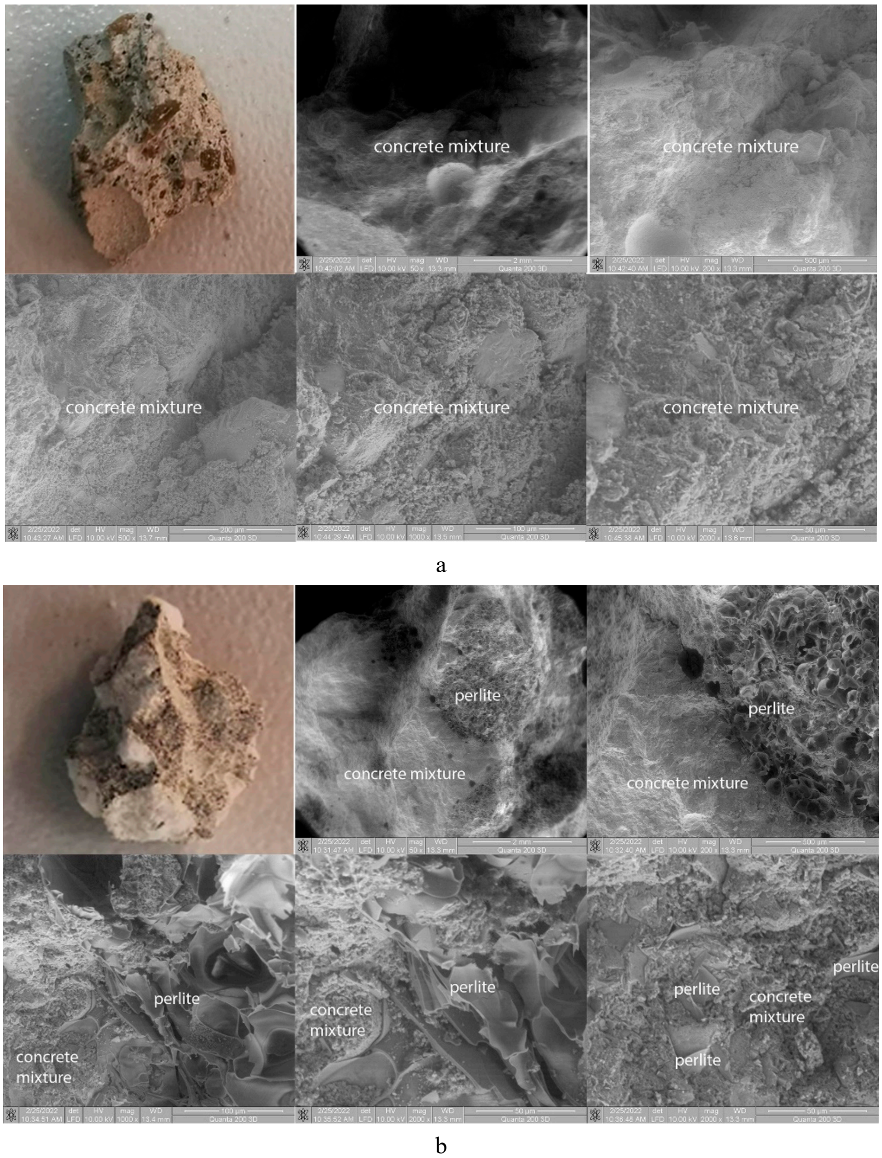


Figure 8. Microscopic images showcasing the analysis of concrete (a) and perlite concrete (b).

4. Discussion

The research studies developed had the intention to present materials used for concrete mixture, which allows for improving its thermal property values.

In part 1, [1], the crumb rubber material was used for the replacement of aggregate in concrete in percentages as 10 %, 20 %, and 30 %. The same laboratory tests were done using the perlite as a replacement for aggregate in concrete samples. In this research stage, a low improvement in the thermal conductivity of perlite concrete was noticed. In the case of the perlite replacements from 10 % to 30 %, the measurement results have varied only from 2.55 W/mK to 2.41 W/mK for heat flow parallel to the casting direction and only from 2.16 W/mK to 2.07 W/mK for heat flow perpendicular to casting direction.

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Because the replacements of 10 %, 20 %, and 30% of 0-4 mm aggregate did not significantly improve thermal conductivity, the measurements made for the replacement of 100 % sand with perlite have been further discussed and analyzed in this paper. The incorporation of 100 % perlite in the concrete mixture resulted in a 15.35 % reduction in density and a 58.30 % and 48.15 % improvement in thermal conductivity for the heat flow parallel to the casting surface and perpendicular to the casting, respectively. However, it is essential to also take into account the compressive strength of the mixture when selecting a mix that improves thermal resistance, as the mixture with the highest amount of perlite (100%) had a compressive strength of 11.49 % lower than the control mixture.

The control concrete composition, class C20/25, typically used for building elements, has a minimum compressive strength of 25 MPa. Replacing perlite with up to 30 % changed the compressive strength value to class C16/C20.

However, due to the lack of significant improvement in thermal conductivity, a new set of control samples was prepared as C16/20 class concrete. The inclusion of 100% perlite resulted in a mixture classified as C12/15 (18.55 MPa), often used in prefabricated concrete blocks.

The results obtained in the linear analysis of the corner thermal bridge for the wall panel made of clay bricks (case I) and of perlite concrete blocks (case II) show that the thermal resistance of the wall with perlite concrete blocks has an insignificant decrease of approximately 3%, which substantiates the proposal for use as a prefabricated masonry element.

The bond between the pearlite-containing regions in the concrete mixture was evaluated using a microscope and was found to be comparable to that of the control concrete. This suggests that the inclusion of perlite in the mix did not have a significant impact on the bond between the concrete components, as seen on magnification. However, it is necessary to mention that the distribution of perlite granules could be affected by a low A/C ratio, and the fresh workability of the concrete could affect the homogeneity of the composition.

5. Conclusion

The present study is part of a larger experimental investigation of incorporating two environmentally friendly materials, perlite and crumb rubber, into cement-based products to enhance their thermal insulation properties and reduce concrete environmental impact.

Based on the results presented in this study, the following conclusion can be drawn:

- Incorporating perlite and crumb rubber into cement-based products shows potential for enhancing thermal insulation properties and reducing environmental impact.
- One of the most significant results of the current study is the improved thermal insulation property of concrete when perlite is used in the composition as a fine part of the aggregates, especially the sort of 0-4 mm.
- The results obtained from the research show that replacing sand with perlite in proportions of 10, 20, and 30 percent lead to the improvement of thermal insulation properties, simultaneously with the reduction of mechanical resistance. However, these results are not in line with expected targets. The advantage obtained for the thermal performance is diminished in importance, being outranked by decreased mechanical resistance.
- The total replacement of sand with perlite (in 100 percent) determines an obvious improvement of the thermal insulation properties, with the undoubted disadvantage of weakening the concrete, slightly under the limit of the C16/C20 concrete resistance class, more precisely, class C12/15.
- Based on these results of the substantial decrease in thermal conductivity and density, as well as a decrease but adequate limits in compressive strength, it can be concluded that for prefabricated concrete blocks used in non-load-bearing walls, concrete with perlite as a 100% substitute for sand, is a solution that can be used successfully, to highly increase the insulated thermal performance of exterior walls.

- Considering the reduced density, this solution has the advantage that the blocks can be made industrially, with certified quality control, and in much larger sizes than concrete blocks or ceramic bricks.
- For one square meter of masonry made of concrete blocks with perlite, the costs can be greatly reduced, compared to one square meter of masonry made with ceramic or concrete blocks through two of its components: the cost of the raw material used and the cost of labor. This financial advantage results from waste perlite being used, and the labor, as a parameter directly proportional to the built time, is reduced due to the increased size of the blocks used for a masonry wall.
- The results also highlighted the ability of the concrete mix components to bond to each other, knowing that this adhesion affects the concrete's overall performance and structural integrity. Inadequate adhesion of components can lead to internal voids or promote concrete cracking, as well as other types of degradation. According to the research results, the samples with perlite showed good compactness, the microscopic imaging highlighting a similar volume of voids compared to normal concrete samples. The samples incorporating crumb rubber revealed a much larger void volume with a low bond of the rubber granules to the concrete aggregates (gravel type), probably on account of the smooth surface of the recycled rubber, as well as due to a low capacity to water absorption for rubber, which obstructs the formation of cement paste hardening compounds in deep contact with the rubber surface.

For a more comprehensive understanding of how the physical-mechanical properties and, in general, the behavior of concrete subjected to different environmental factors/actions are affected by incorporating possible wastes in its compositions, further studies are needed. The design of the compositions, as well as the research of the characteristics of the concrete product, according to the standard quality requirements, have to take into account the influence of several variables defined as material properties, geometry characteristics, or environmental factors. The results led to the construction industry's adaptation to new materials without causing damage to the main function of the construction, that of resistance and stability.

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